Photovoltaic Technology Development and Capabilities at GRC

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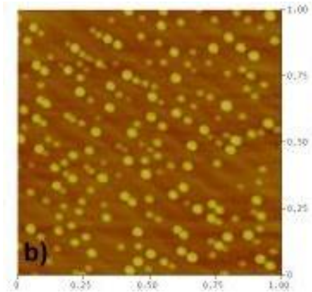
USAF/SMC OCS Briefing at NASA GRC
January 17, 2018

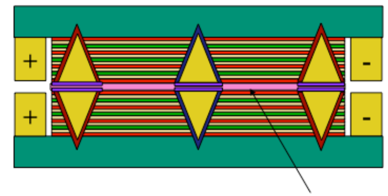
Photovoltaic (PV) Areas of Expertise

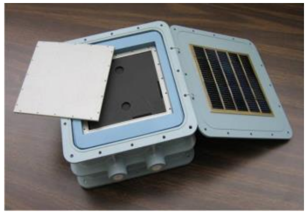
High Efficiency III-V Photovoltaic Development

Nanomaterials and Nanostructures for Space Photovoltaics

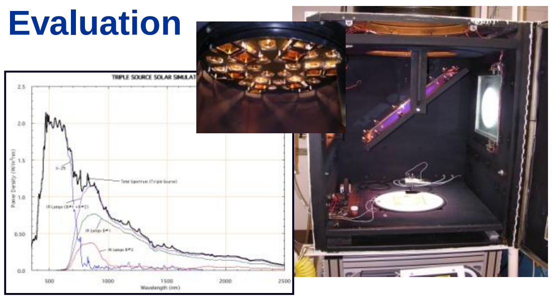


Radioisotope-based Direct Energy Conversion (Thermophotovoltaic and Alpha/Beta-voltaic Technology)





Solar Cell Measurement and Performance Evaluation



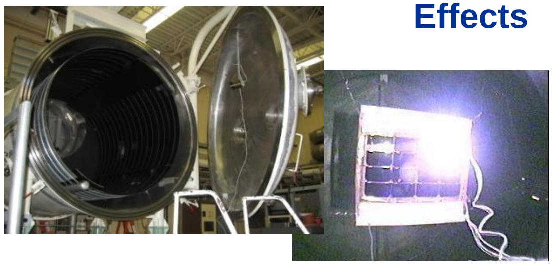
Research and development on a wide variety of solar cell, blanket component, and array concepts to support NASA missions and aerospace technology needs.

Extreme Environment Operation of Solar Arrays

Solar Cell Air Mass Zero Calibration

Advanced Blanket and Array Technologies

Solar Array Arcing and Charging Effects

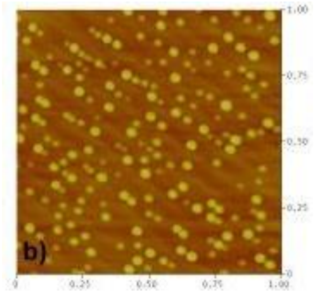


PV Supports Broad Range of TRL Activities

TRL 2-4

Examples:

- NASA Institute for Advanced Concepts (NIAC) studies, Small Business Innovation Research (SBIR) contracts, student and faculty fellowships, etc.
- Focused on PV materials & novel designs for improved efficiency, radiation resis-tance, temp. extremes, etc.
- High temp. cells, perov-skites, low-cost substrates

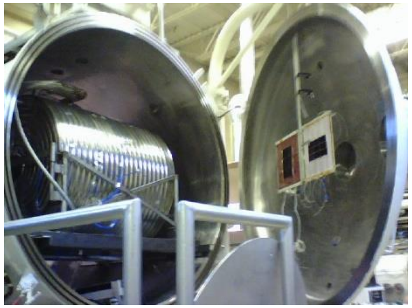


InAs Quantum Dots in GaAs cells

TRL 5-6

Examples:

- Advanced Technology Performance, Reliability, and Environmental Interactions R&D and Evaluation



Thermal balance & arcing of blanket technology

Accurate cell efficiency measurements

TRL 7-9

Examples:

- Support NASA Missions Through Technical Expertise
- Evaluate Flight Data for New Technology
- Development of Standards and Guidelines

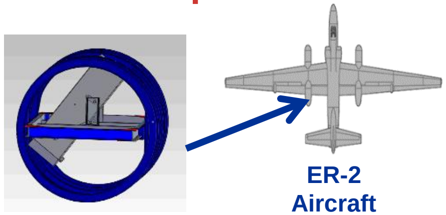
SCARLET array on Deep Space 1

Mars Rover Experiments

World Class Capabilities in PV

Expert physicists, chemists, and engineers with extensive experience in solar cell fabrication and solar array operation within the space environment. World experts in materials growth, device fabrication, cell measurement and characterization, and coupon/array environmental testing. Partners range from universities, non-profit organizations and small/large businesses to various NASA Centers and other Government agencies.

Lear upgraded to ER-2 aircraft for Calibration Flights to provide cell standards for the aerospace community



OMVPE Reactors for growth of high efficiency solar cells

X25 Solar Simulator and new LED Simulator for accurate measure-ments of solar cell performance

PIF (Plasma Interactions Facility) for testing of solar arrays within a space environment

Thermal Balance Testing for Lightweight Blankets

NASA Thrusts in Power Technology Development

1) Power for Human Surface Missions

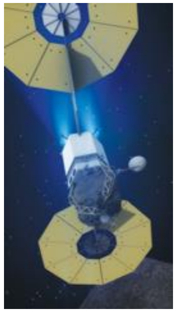
Stationary Power:
40 kW continuous power, day & night
High system specific power >5 W/kg
Nuclear fission or PV with energy storage
Human-rated (safety and fault tolerance)
Robotically-deployed (pre-crew arrival)
Survivable for multiple crew campaigns >10 yrs

Mobile Power:
6 to 10 kW rechargeable power, up to 120 kWh
Advanced batteries/fuel cells >300 Wh/kg, >200 cycles
Maximum commonality with other surface assets
Grid-compatible (with stationary power)

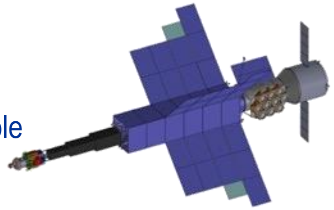
Both: Mars gravity, wind, dust, CO_2, temperature, diurnal period

2) Power for Electric Propulsion

Near Earth Systems:
30 to 50 kW solar array wings >100 W/kg
Compact array stowage >40 kW/m3
High deployed strength >0.1g and frequency >0.1 Hz
High operating voltage >160V, PPU-compatible
Long life >7 yrs with reuse



Mars and Beyond:
100 to 300 kW solar array wings >150W/kg
Radiation tolerant solar cells
Compact array stowage >60 kW/m3
1 to 5 MW fission reactors <5 kg/kW
High operating voltage >300V, PPU-compatible
Long life >5 yrs (Earth to Mars)



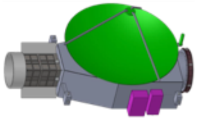
3) Power for Robotic Science Probes

Orbiters, Landers & Rovers:
Power levels from 100 to 600 W at EOM
Possibly kWs for ice melting, comm relays, EP
Very long life >10 yrs and high reliability
Low mass power systems >5 W/kg
High performance RPS/fission >15% eff.
Low intensity/low temperature PV >25% eff.
Advanced batteries >300 Wh/kg, >200 cycles
Extreme environments (low/high temperature, low/high solar intensity, high radiation)

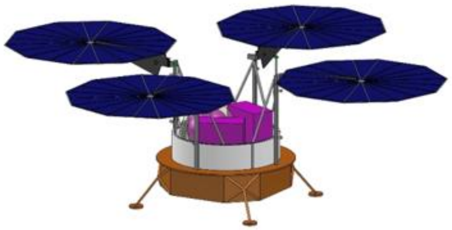
4) Power for Small Spacecraft

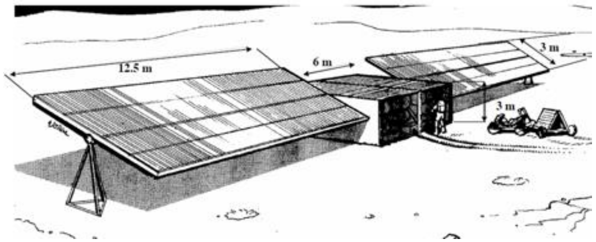
Near Earth Systems:
Power levels from 100 to 500W
Body-mounted or deployable solar arrays >200 W/kg
Advanced batteries >200 Wh/kg, >200 cycles
Compatible with 2U to 24U Cubesat platforms
Highly integrated systems with shared structure

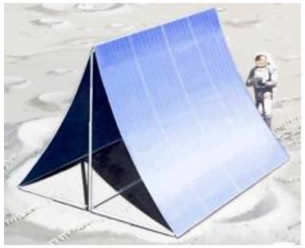
Deep Space Systems:
Power levels from milliwatts up to 60W (nuclear)
Small RPS using multiple RHUs or single GPHS
Advanced conversion (TE, Stirling, Alpha/Beta-voltaic) >15% eff

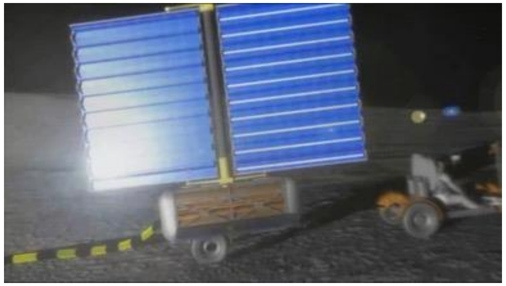


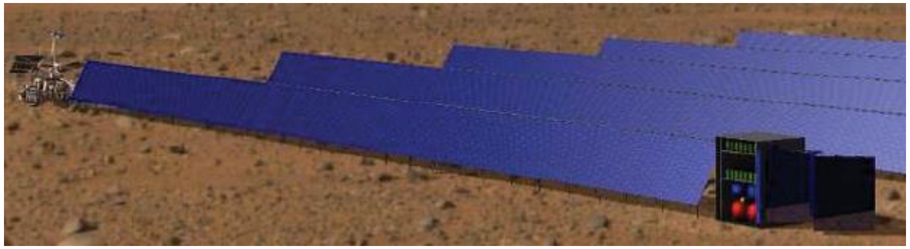
Mars Surface PV Array Concepts Evaluated

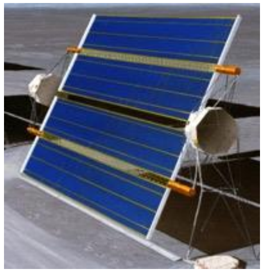


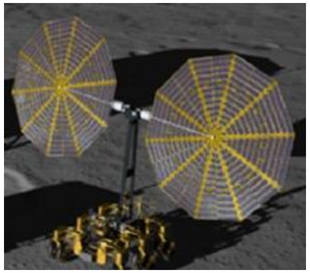








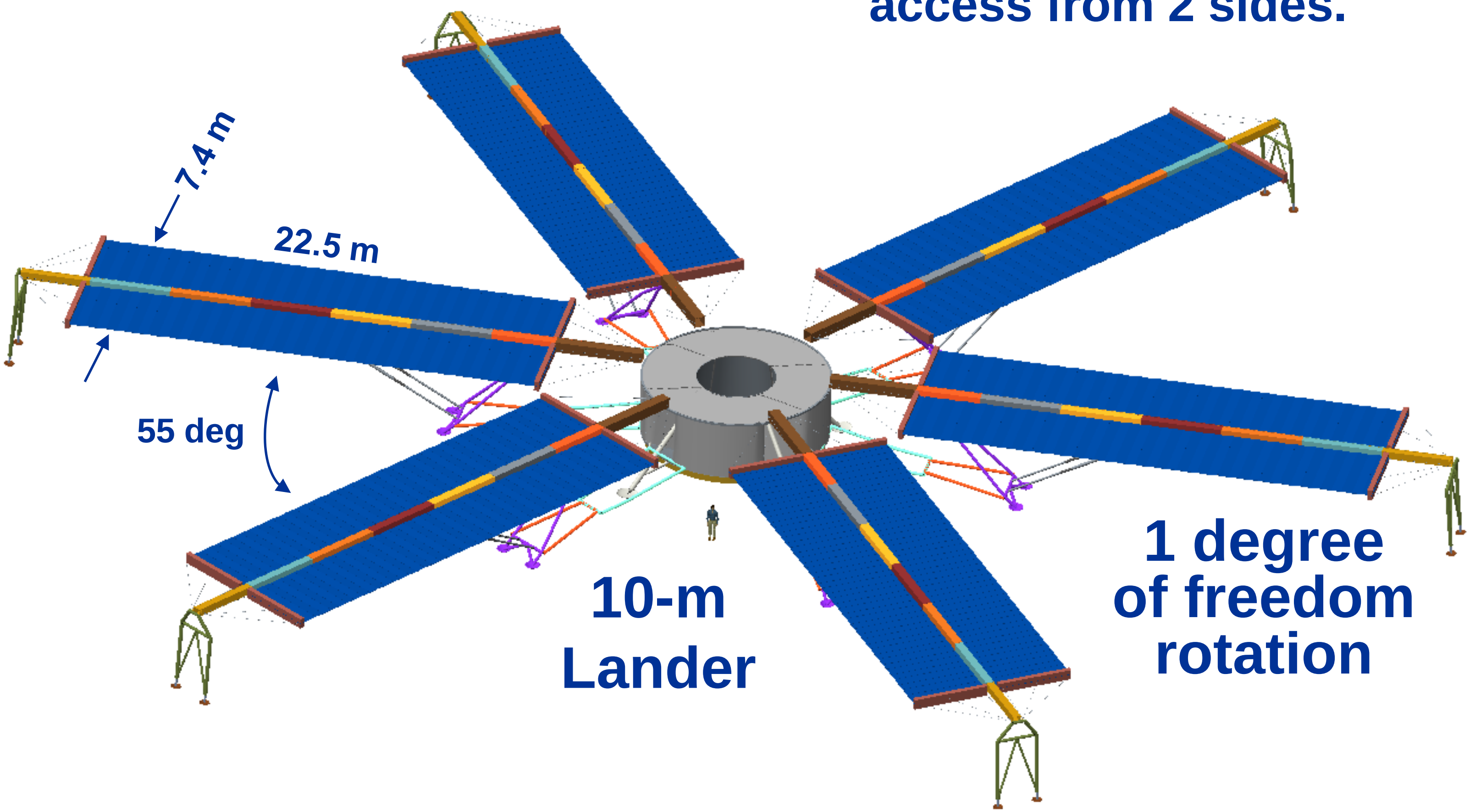




Mars Surface Lander Baseline Design Using Six Solar Array Wings

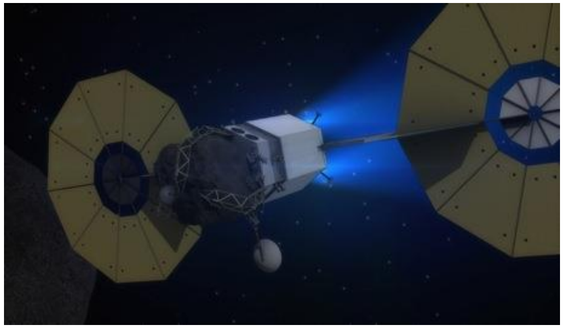
1000 m^2 total solar cell area.

Array spacing allows cargo access from 2 sides.



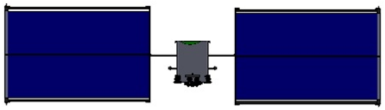
Surface array design based on Compact Telescoping Array concept

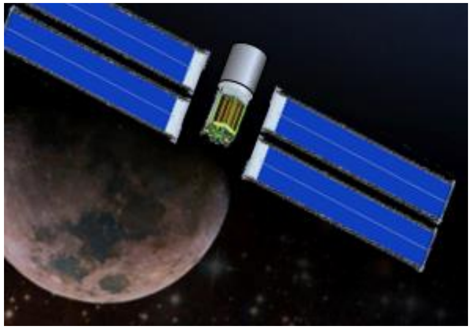
Power for Solar Electric Propulsion (SEP)



Initial SEP Capability (SEP Technology Demo)

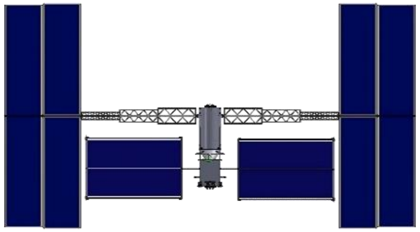
- 50-kW Solar Array System
- 40-kW EP System
- 5-t class Xenon Capacity with Refueling Capability
- 13-kW EP strings

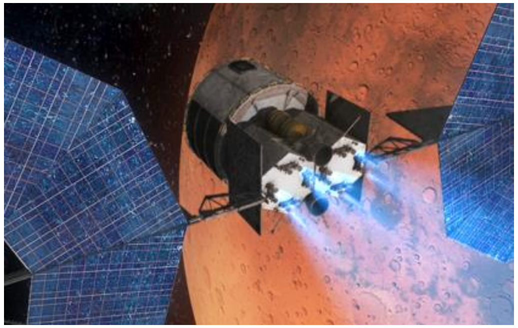




Proving Ground Or Split Mars Architecture

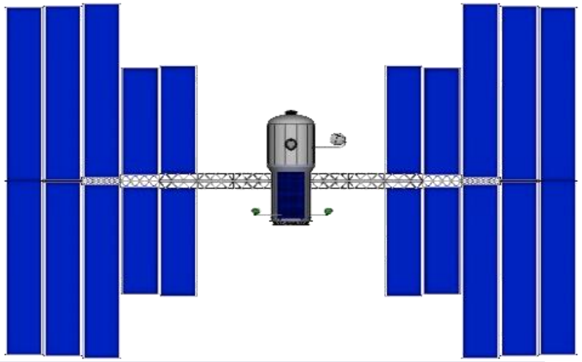
- 190-kW Solar Array
- 150-kW EP System
- 16-t class Xenon Capacity
- 13-kW EP strings





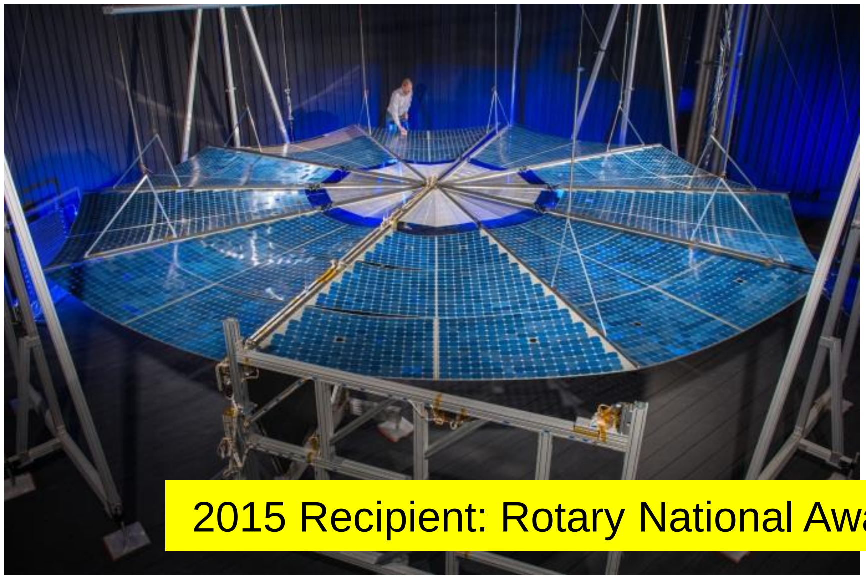
Hybrid Mars Architecture

- 400-kW class Solar Array
- 300-kW class EP System
- 16-t class Xenon Capacity
- 30-kW class EP strings

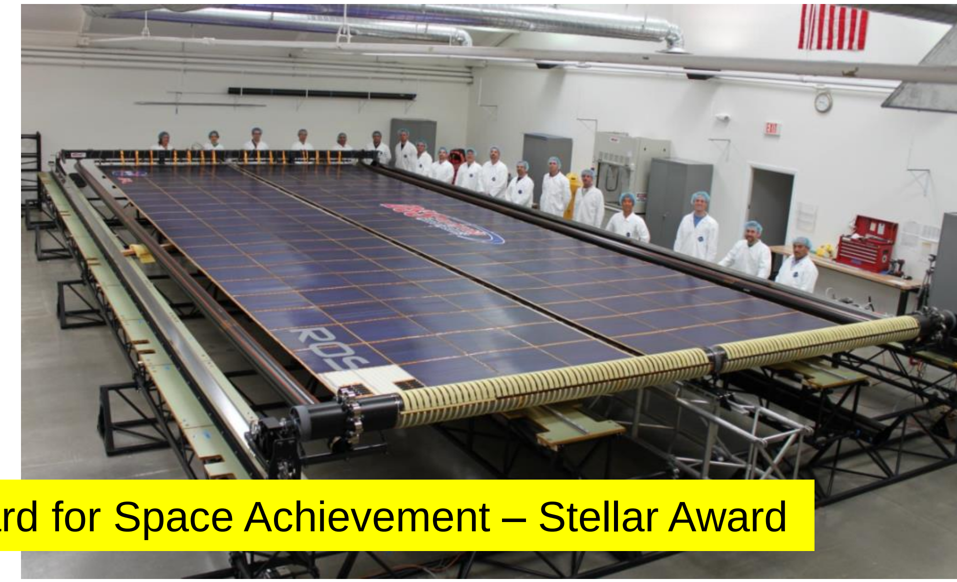


Electric Propulsion (EP) Solar Array Systems

ATK MegaFlex



DSS Roll Out Solar Array (ROSA)



2015 Recipient: Rotary National Award for Space Achievement – Stellar Award

- Novel 20 kW-class solar arrays designed & built to advance TRL from 4 to 5+ for SEP missions; extensible to 300 kW class (>$12M invested on two contracts)
- Testing included: stowed acoustic/random vibration, thermal extreme vacuum deployments, deployed strength/stiffness, deployed structural dynamics in ambient & vacuum, PV coupon plasma interactions up to 600 V in ambient and EP plasma plume
- Improvement to state-of-the-art: power, voltage, mass, stowed volume, deployed strength/stiffness, radiation hardness

Power for Robotic Science Probes

- **Key for robotic science is long life, reliable power**
  - Plutonium-powered RTGs have been staple for >40 yrs but fuel availability, integration costs, schedule risk, & launch safety are impediments
  - Solar power is starting to win power trades (e.g. JUNO, Solar Probe Plus, Europa Clipper)
- **Expected end-of-mission power requirement is 100 to 600 We**
  - Possibly kWs for ice melting, communication relays, electric propulsion
  - Need low mass power systems >5 W/kg and high conversion efficiency >15% nuclear, >25% solar
- **Higher power provides path to increased capabilities**
  - More instruments, increased duty cycles
  - High rate communications, real time tele-operations, in-situ data analysis
  - Sufficient on-board power for subsurface science (e.g. ice melting)
  - Integration with EP for lower launch mass, and multiple targets with single spacecraft
- **Upcoming mission applications**
  - Europa Clipper/Europa Lander
  - New Frontiers 2024, Discovery 2028
  - Future Flagships: Titan Saturn System Mission, Uranus Orbiter Probe, Neptune Systems Explorer, Saturn Ring Observer, …

Extreme Environments Solar Power (EESP)

- EESP Project seeks to develop solar cell/solar array technologies for mission applications in high radiation and low solar flux environments
  - Investigate PV cell chemistry improvements for low intensity, low temperature (LILT) environments
  - Investigate array configuration options that improve performance in extreme environments
  - Increase array efficiency & life; decrease system mass & cost

- Four Base Contracts Awarded (July 2016)
  - Concentrator Solar Power Systems for Low-intensity Low Temperature and High Radiation Game Changing Technology Development, **Orbital ATK**
  - Transformational Solar Array for Extreme Environments, **JHU/Applied Physics Lab**
  - Micro-Concentrator Solar Array Technology for Extreme Environments, **Boeing**
  - Solar Array for Low-intensity Low Temperature and High-Radiation Environments, **NASA JPL**

- Selection of Two Contract Options for Continued Development after Base Contracts

Key Performance Parameters			
Performance Parameter	State of the Art	Threshold Value	**Project Goal**
*Beginning of Life (BOL) Cell Efficiency (%)	30	33	**35**
*End of Life (EOL) Cell Efficiency (%)	21	25	**28**
Specific Power (W/kg)	70	100	**120**
Stowed Volume (kW/m^3)	15-30	45	**60**

*at the following mission conditions: -125°C, 4E15 1MeV e/cm^2 Radiation, 50 W/m^2 Solar Intensity

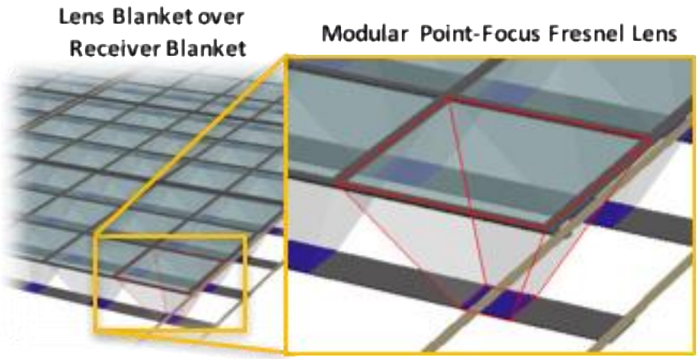
EESP Option 1 Contract Awards

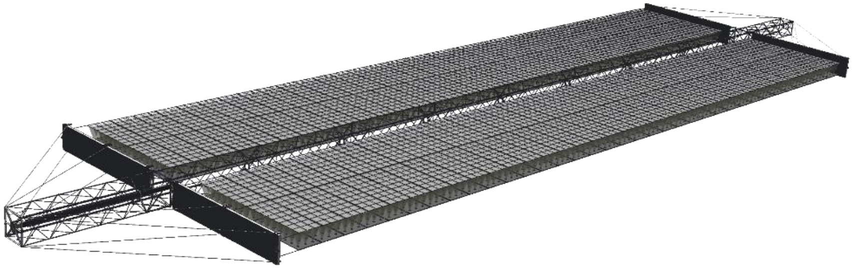
Johns Hopkins Univ. Applied Physics Lab

DSS Roll Out Solar Array (ROSA) equipped with Flexible Array Concentrator Technology (FACT) and Inverted Metamorphic solar cells

Orbital ATK

Point-focus lens concentrator blanket compatible with the Compact Telescoping Array (CTA) platform utilizing state of the art ZTJ solar cells





Power for Small Spacecraft

Small Spacecraft Power

- Growing trend to fly greater number of small missions versus one or two large missions
- Small satellites can provide cost benefits and greater access to space
- Advanced power technologies are crucial to the small satellite and CubeSat market segment
- Power system improvements can increase available power, extend mission life, and/or allow greater payload mass

Current State of the Art:

- Commercial solar arrays with >28% efficiency
- Commercial Li-ion batteries at ~150 Whr/kg
- Commercial plug and play power distribution boards and electrical controllers
- Poor reliability – high failure rates

Power Challenges:

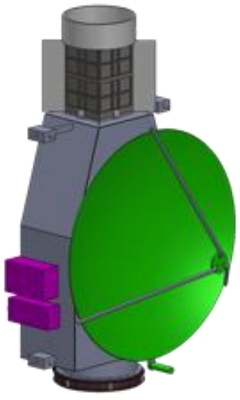
- Highly integrated systems with shared structure and thermal management
- Improved performance, increased reliability, decreased recurring cost
- Low cost power options for beyond Low Earth Orbit

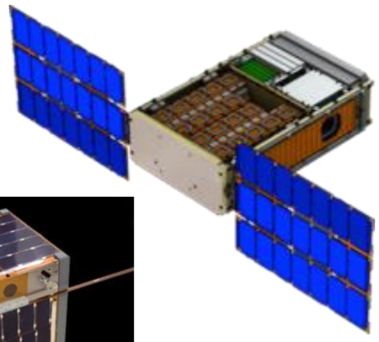
Near Earth Technology Needs:

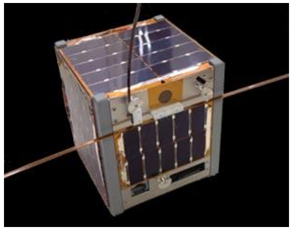
- Power levels from 100 to 500W
- Body-mounted or deployable arrays >200 W/kg
- Advanced batteries >200 Wh/kg, >200 LEO cycles
- Compatible with 2U to 24U CubeSat platforms

Deep Space Technology Needs:

- Power levels from milliwatts up to 60W (nuclear)
- Small RPS using multiple Radioisotope Heater Units (RHU) or single General Purpose Heat Source (GPHS)
- Advanced conversion, e.g. thermoelectric, Stirling, thermo-photovoltaic, alpha/beta-voltaics >15% eff







State-of-the-Art Space Photovoltaics

- Major US cell suppliers are SolAero Technologies and Spectrolab
  - Nominally 30% in-space conversion efficiency
  - Gallium arsenide-based multijunction (3-junction) solar cell technology
  - Fully space-qualified
  - Designed for End-of-Life (EOL) performance (within the space radiation environment)
  - VERY EXPENSIVE (compared to terrestrial solar cells)

Space solar cell

Industry Diversification into Terrestrial Photovoltaics

- Adaptation of space cell technology for terrestrial PV systems
  - Minor changes to space cell design, but essentially the same technology
  - Addressed high cell cost thru concentrator applications (> 1000 suns)

Terrestrial concentrator cells

Terrestrial PV Technology of Interest to NASA

- Application of low-cost solar array blanket manufacturing methods and terrestrial solar cell technology for space missions
  - Automated manufacturing and modularity
  - SpaceX use of silicon PV terrestrial technology for short duration missions
  - Focus is on ”lower cost” cell technology
  - NASA has conducted in-space flight experiments of terrestrial PV to evaluate long-term survivability under NASA mission requirements (with mixed results)
- Use of lower cost epitaxial grow techniques for gallium arsenide-based higher efficiency solar cells
  - Hydride Vapor Phase Epitaxy (HVPE) growth techniques being developed at National Renewable Energy Laboratory (NREL)
- Renewed interest in perovskite solar cell technology
  - Potential for high efficiency terrestrial technology at lower fabrication costs
  - Recent test results indicate potential for in-space radiation hardness

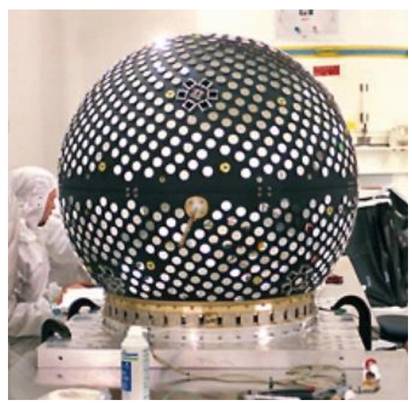
Examples of Terrestrial PV for Space Applications

- MicroLink Devices (MLD)
  - Uses GaAs multijunction solar cell technology similar to space
  - Focus is on reducing solar cell cost (> 50%) while maintaining high efficiency
    - Epitaxial Lift Off (ELO) technique used to reduce mass and cost
    - Wafer substrate is recycled/reused to reduce substrate cost
  - Current terrestrial uses include increasing flight endurance of Raven UAV and battery recharge capability in the field. Space applications involve substrate reuse to reduce cost/mass and "rollable" blankets.
    - Mission use requires flight qualification of technology
    - Primarily via SBIR funding

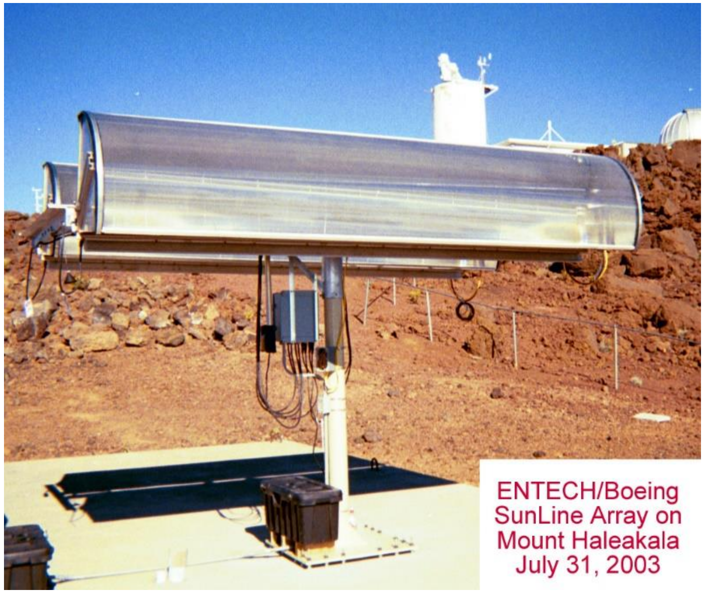
Current uses of MLD ELO cell technology

- Starshine-3 Flight Exp.
  - Integrated Micropower Systems (IMPS): were successfully flown aboard Starshine-3 and provided continuous power for on-board temperature sensors.

Starshine-3

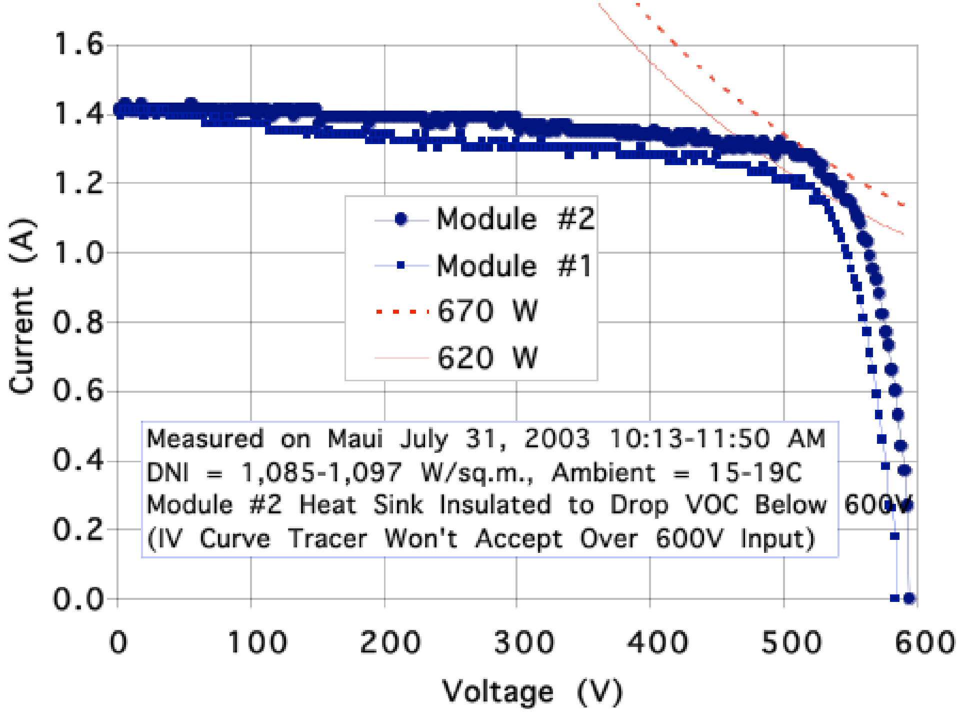


ENTECH High-Voltage *SunLine* on Mt. Haleakala (Maui) Power source used in NASA GRC-funded Power Beaming Experiment



ENTECH/Boeing SunLine Array on Mount Haleakala July 31, 2003

Each Concentrator Module Uses a 3 m^2 Color-Mixing Lens to Focus Sunlight at 26X Concentration onto a Boeing/Spectrolab Triple-Junction Cell Receiver



Measured IV Curves for Both Modules – Note that the Better Module (670 W) Had to Have Its Heat Sink Insulated to Enable this Measurement

Boeing Developed the Photovoltaic Receivers for this Test
– the First-Ever Terrestrial Multi-Junction-Cell Array Over 1 kW

Dual-Use Technology: From Ground Technology to Space Technology to Improved Ground Technology Winning R&D 100 Award

Improved ground photovoltaic concentrator technology called **SolarVolt** uses small (15 cm wide) Fresnel lenses focusing onto small (0.75 cm wide) silicon cells as shown in array on left with older large lens technology on right. **SolarVolt** is much lighter and cheaper than the old large lens technology, due to lessons learned from the **Stretched Lens Array** for space. **SolarVolt** won an **R&D 100 Award in 2012** for **NASA GRC** and **Entech Solar**.

In Summary

- GRC covers a wide range of PV technologies and TRL levels
- Focus is on NASA-specific space PV technology development with unique in-space mission requirements
  - Leverage existing commercial space PV where possible
  - Monitor terrestrial PV developments for NASA use where appropriate
- Collaborate closely with Air Force, Navy, and OGA efforts
  - Interagency Advanced Power Group, Small Business (SBIR) contract reviews, grant/student programs, etc.
- Tours on advanced cell/array development and solar cell measurements and calibration are available upon request